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Key Points:
- CMIP3, CMIP5, and CMIP6 models share similar systematic annual multi-model ensemble mean precipitation errors in the tropics
- The annual double-ITCZ bias and its big inter-model spread persist in CMIP3/5/6 models but are slightly reduced from CMIP3/5 to CMIP6
- The annual equatorial Pacific cold tongue bias persists in CMIP3/5/6, but its inter-model spread is reduced from CMIP3 to CMIP5 and to CMIP6

Supporting Information:
- Supporting Information S1

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The Double-ITCZ Bias in CMIP3, CMIP5, and CMIP6 Models Based on Annual Mean Precipitation

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Abstract The double-intertropical convergence zone (ITCZ) bias is one of the most outstanding errors in all previous generations of climate models. Here, the annual double-ITCZ bias and the associated precipitation bias in the latest climate models for Coupled Model Intercomparison Project (CMIP) Phase 6 (CMIP6) are examined in comparison to their previous generations (CMIP Phase 3 [CMIP3] and CMIP Phase 5 [CMIP5]). All three generations of CMIP models share similar systematic annual multi-model ensemble mean precipitation errors in the tropics. The notorious double-ITCZ bias and its big inter-model spread persist in CMIP3, CMIP5, and CMIP6 models. Based on several tropical precipitation bias indices, the double-ITCZ bias is slightly reduced from CMIP3 or CMIP5 to CMIP6. In addition, the annual equatorial Pacific cold tongue persists in all three generations of CMIP models, but its inter-model spread is reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6.

Plain Language Summary The double-intertropical convergence zone (ITCZ) bias is one of the most outstanding errors in all previous generations of climate models that may reduce the reliability of future climate prediction based on these models. The models have two ITCZs (i.e., zonally elongated narrow belt of high precipitation) in both hemispheres, over the equatorial central and eastern Pacific and Atlantic, instead of one ITCZ over the northern hemisphere in observations except for a short period in March and April. Here, we examine such bias in the latest models for Coupled Model Intercomparison Project (CMIP) Phase 6 (CMIP6) based on long-term annual mean precipitations in observations and models and compare the biases among the recent three generations of CMIP models (CMIP3, CMIP5, and CMIP6). We find that the double-ITCZ bias with a big inter-model spread persists in all CMIP models and still remains a serious problem in the latest CMIP6 models. However, the bias is slightly reduced in CMIP6 models from CMIP3 or CMIP5 models based on several precipitation bias indices. In addition, the annual equatorial Pacific cold tongue bias also persists in all CMIP models, but its inter-model spread is reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6.

1. Introduction

The Coupled Model Intercomparison Project (CMIP) (Meehl et al., 2005) collects and archives multiple climate model outputs in a standardized format to make them publicly available by the community and users and has become a central element of national and international assessments of climate change. For example, the CMIP Phase 3 (CMIP3) (Meehl et al., 2007) and Phase 5 (CMIP5) (Taylor et al., 2012) multi-model data sets have played an essential role for the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports (AR4 and AR5) (IPCC, 2007, 2013), respectively. The latest state-of-the-art climate model outputs from CMIP Phase 6 (CMIP6) (Eyring et al., 2016) will be the foundation for the upcoming IPCC Sixth Assessment Report (AR6). To increase confidence in future climate projections and the fidelity of IPCC AR6, CMIP6 model experiments need rigorous evaluation (e.g., Flato et al., 2013; Randall et al., 2007; Tian, 2015).

The intertropical convergence zone (ITCZ) (Schneider et al., 2014; Waliser & Gautier, 1993) is a zonally elongated narrow band of surface convergence zone with heavy precipitation and deep convective clouds located over the equatorial Indo-Pacific warm pool, the Northern Hemisphere (NH) central and eastern Pacific, the equatorial Amazonia, the NH Atlantic, and the equatorial Africa. In particular, the ITCZ is found only in the NH 4–12° latitude belt over the central and eastern Pacific and the Atlantic. The South Pacific convergence zone (SPCZ) (Haffke & Magnusdottir, 2013; Vincent, 1994) is a surface convergence zone in the Southern

Hemisphere (SH) oriented in a northwest-southeast manner extending from the Indo-Pacific warm pool to the south central Pacific(Haffke & Magnusdottir, 2013; Mamalakis & Foufoula-Georgiou, 2018). Similar northwest-southeast oriented surface convergence zones also exist in the SH Atlantic and Indian Oceans. The South Atlantic convergence zone (SACZ) (Carvalho et al., 2004) extends from South America to the southwest Atlantic Ocean while the South Indian Ocean convergence zone (SIOCZ) (Cook, 2000; Lazenby et al., 2016) extends from the South Africa to the southwest Indian Ocean. There is no ITCZ or zonally oriented surface convergence zone over the southeastern Pacific and South Atlantic in the SH except for a short period in March and April (Bischoff & Schneider, 2016; Haffke et al., 2016; Yang & Magnusdottir, 2016; Zhang, 2001).

The vast majority of fully coupled global climate models (simply [climate] models, same thereafter), however, have a spurious ITCZ or zonally oriented surface convergence zone over the southeastern Pacific and South Atlantic (~10°S) parallel to the equator resembling its NH counterpart particularly in boreal winter (SH rainy season) and reducing the hemispheric asymmetry of the ITCZ distribution. This double-ITCZ bias has been a long-standing tropical bias in the climate models since the early days of their development (Mechoso et al., 1995). It still remains a serious problem in the climate models for the last two CMIPs: CMIP3 (e.g., Bellucci et al., 2010; De Szoeke & Xie, 2008; Hirota et al., 2011; Lin, 2007) and CMIP5 (e.g., Adam et al., 2018; Hwang & Frierson, 2013; Li & Xie, 2014; Tian, 2015; Xiang et al., 2017; Zhang et al., 2015).

The purpose of this study is to examine the double-ITCZ bias, its inter-model spread, and its possible progress in CMIP6 models in comparison to their previous generations of CMIP models (CMIP3 and CMIP5) based on long-term annual mean precipitations in observations and models. The rest of this paper is organized as follows. Section 2 describes data and methodology. Section 3 presents the main results of this study followed by a summary in section 4.

2. Data and Methodology

2.1. Observational Data

For observations, we use the Global Precipitation Climatology Project (GPCP) (Adler et al., 2003) and Tropical Rainfall Measurement Mission (TRMM) (Huffman et al., 2007) monthly mean precipitation flux (pr) data sets available on the Observations for Model Intercomparison Projects (Obs4MIPs) (Ferraro et al., 2015; Teixeira et al., 2014) website (Adler & Huffman, 2018; Huffman, 2018). The GPCP data are from January 1979 to October 2017 on the $2.5° \times 2.5°$ spatial grid while the TRMM data are from January 1998 to December 2013 on the $0.25° \times 0.25°$ spatial grid.

2.2. Model Data

Monthly mean precipitation flux (pr) outputs from January 1850 to the latest (December 2000 for CMIP3, December 2005 for CMIP5, and December 2014 for CMIP6) from the "20th century" (CMIP3) or "historical" (CMIP5/6) experiments of 75 climate models for CMIP3, CMIP5, and CMIP6 are analyzed in this study (Eyring et al., 2016; Meehl et al., 2007; Taylor et al., 2012). These include 24 CMIP3 models and 25 CMIP5 models mostly from Tian (2015) and 26 CMIP6 models currently available (supporting information Table S1). If available, the first ensemble member run of variant label "r1i1p1" for CMIP3/5 and "r1i1p1f1" for CMIP6 are used. Here, r1 is realization index, i1 initialization index, p1 physics index, and f1 forcing index (Taylor et al., 2018). Different models have different atmospheric spatial resolutions (Table S1). Some CMIP6 models do not have a "CMIP5 version," and some CMIP5 models do not have a "CMIP3 version." It is therefore hard to gauge the "progress" made from CMIP3 to CMIP5 and from CMIP5 to CMIP6.

2.3. Analysis Methodology

Following Tian (2015), the long-term annual means of model precipitation are calculated from the last 20-year monthly mean precipitation outputs: January 1981–December 2000 for CMIP3, January 1986–December 2005 for CMIP5, and January 1995–December 2014 for CMIP6. The long-term annual means of observational precipitation are calculated from January 1995 to December 2014 using the GPCP data to match the CMIP6 model data record and from the whole TRMM data period (January 1998 to December 2013). Due to the different spatial grids of different observational and model data sets, we re-grid all the observational and model precipitation data onto the GPCP $2.5° \times 2.5°$ spatial grid for easy comparisons.

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2.4. Double-ITCZ Bias Indices

To quantify the double-ITCZ bias in CMIP3/5/6 models, several double-ITCZ bias indices are used here: The tropical precipitation asymmetry index (TPAI), the equatorial precipitation index (EPI), the southern ITCZ index over the Pacific (SIIP), and the southern ITCZ index over the Atlantic (SIIA). The TPAI is the difference between the NH tropical mean precipitation (equator to 20°N, area averaged) and the SH tropical mean precipitation (equator to 20°S, area averaged) normalized by the tropical mean precipitation (20°S to 20°N, area averaged) (Hwang & Frierson, 2013). The larger the model TPAI, the smaller the double-ITCZ bias is. The EPI is the ratio of the equatorial mean precipitation (2°S to 2°N) and the tropical mean precipitation (20°S to 20°N) (Adam et al., 2016, 2018). The larger the model EPI, the smaller the equatorial Pacific cold tongue bias is and thus the smaller double-ITCZ bias is. To explore the regional difference, we add the TPAI and EPI over the Pacific (120–80°W) and Atlantic (40°W–0°) in addition to the global ones and call them as the global, Pacific, and Atlantic TPAI and EPI, respectively. The SIIP is defined as the model long-term annual mean precipitation bias (model-observation, mm day^{-1}) over the southeastern Pacific (30°S to equator, 150–100°W) (area averaged) (e.g., Bellucci et al., 2010; Hirota et al., 2011; Tian, 2015). The larger the model SIIP, the larger the double-ITCZ bias over the Pacific is. Similarly, the SIIA is defined as the model long-term annual mean precipitation bias (model-observation, mm day^{-1}) over the South Atlantic (20°S to equator, 35°W–0°) (area averaged). The larger the model SIIA, the larger the double-ITCZ bias over the Atlantic is.

3. Results

Figures 1a and 1b show the long-term annual mean precipitation (mm day^{-1}) over the global tropics (30°S to 30°N) (thereafter) from two observations: (a) GPCP and (b) TRMM. GPCP and TRMM show a consistent familiar observational precipitation and ITCZ pattern with a very high linear Pearson correlation between them (R^2 = 0.96). The ITCZ as indicated by a zonally oriented high precipitation band is located over the equatorial Indo-Pacific warm pool, the NH (4–12°N) central and eastern Pacific, the equatorial Amazonia, the NH (4–12°N) Atlantic, and the equatorial Africa. High precipitation is also found over the SH south central Pacific associated with the SPCZ, over the SH southwest Atlantic associated with the SACZ, over the SH southwest Indian Ocean associated with the SIOCZ, and over the northwestern Pacific and the northwestern Atlantic extending to the mid-latitudes. There is no ITCZ over the southeastern Pacific and the South Atlantic in the SH (Waliser & Gautier, 1993). There are some differences between the GPCP and TRMM precipitation magnitude which indicates the observational precipitation uncertainty. For example, TRMM is higher than GPCP over the equatorial Indo-Pacific warm pool. The underlying relative bias error (RBE) (unitless) of the GPCP and TRMM precipitation data is 10–15% in the tropical western Pacific and as large as 20% over the tropical eastern Pacific (Adler et al., 2012; Huffman et al., 2007). Thus, we use the average of GPCP and TRMM precipitations as our best observational precipitation estimate (referred to as "observation") (Figure 1c) and use 20% as its uncertainty (RBE, unitless) in all tropical oceanic grid points to be on the conservative side. As expected, the linear correlation between GPCP (TRMM) and the "observation" is very high (R^2 = 0.98).

The long-term annual mean precipitations over the global tropics from the three generations of CMIP multi-model ensemble means (MMEMs)—(d) CMIP3, (e) CMIP5, and (f) CMIP6—are shown in Figures 1d–1f. There is a strong similarity in the global tropical precipitation patterns among CMIP3/5/6 models (Figures 1d1f) with a high correlation among them (R^2 = 0.98 between CMIP3 and CMIP5, R^2 = 0.98 between CMIP5 and CMIP6, and R^2 = 0.94 between CMIP3 and CMIP6). This indicates that all three generations of CMIP models share similar important successes and troublesome systematic errors. The correlation of the precipitation patterns between models and observations is also high (R^2 = 0.77 for CMIP3, R^2 = 0.79 for CMIP5, and R^2 = 0.83 for CMIP6), indicating the models tend to capture the long-term annual mean precipitation pattern in observations reasonably well, such as the ITCZ over the equatorial Indo-Pacific warm pool, the NH central and eastern Pacific, the equatorial Amazonia, the NH Atlantic, and the equatorial Africa as well as the SPCZ, SACZ, and SIOCZ in the SH. However, several systematic precipitation errors are obvious in Figure 1. First, the model simulated ITCZ over the NH Pacific Ocean tends to be located too north and too wide in comparison to observations. Second, the model simulated SPCZ extends too much eastward to the south central and eastern Pacific and forms a spurious ITCZ

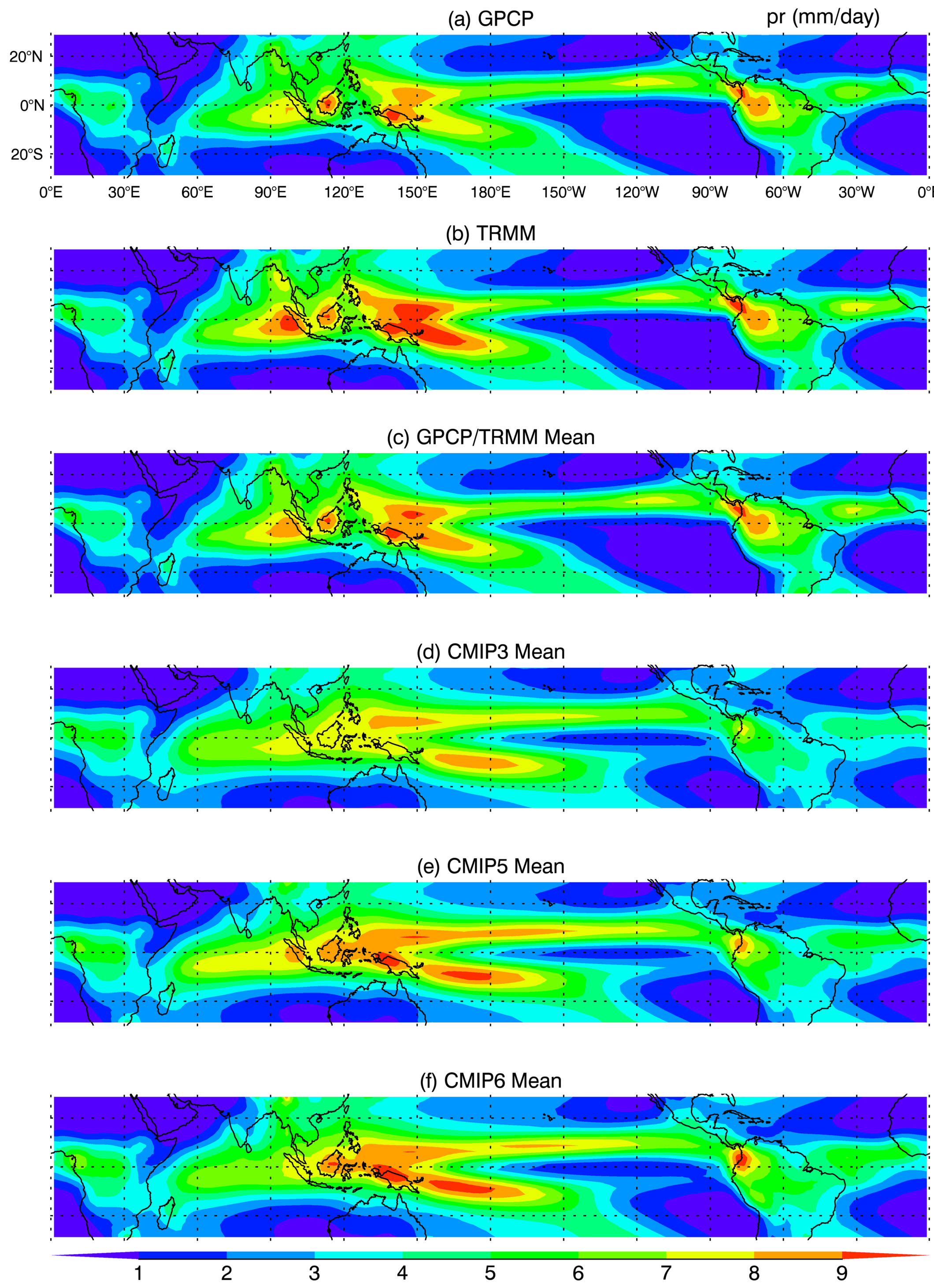

Figure 1. Long-term annual mean precipitation (mm day^{-1}) over the global tropics (30°S to 30°N) from (a) GPCP, (b) TRMM, (c) GPCP/TRMM mean, (d) CMIP3 multi-model ensemble mean (MMEM), (e) CMIP5 MMEM, and (f) CMIP6 MMEM.

there. As a result, there are two ITCZs in the models over the tropical central and eastern Pacific: one over the NH (~10°N) and another one over the SH (~10°S). This is the notorious double-ITCZ bias in the models (e.g., Adam et al., 2018; Hwang & Frierson, 2013; Li & Xie, 2014; Lin, 2007; Mechoso et al., 1995; Tian, 2015; Xiang et al., 2017; Zhang et al., 2015). This indicates the double-ITCZ bias evident in CMIP3/5 models persists in CMIP6 models. Third, the model simulated equatorial Pacific cold tongue as indicated by the low equatorial precipitation tends to be too strong, too narrow, and extend too far west in comparison to observations (Li & Xie, 2014). This indicates the notorious equatorial Pacific cold tongue bias evident in CMIP3/5 models also persists in CMIP6 models. Fourth, the model simulated precipitation over the Maritime Continents is generally too smooth spatially which cannot resolve the inhomogeneous spatial structure induced by the complex local land-sea distribution in observations. Fifth, the model simulated Atlantic ITCZ tends to be located too southward in comparison to observations.

To further highlight the model and observation differences, the long-term annual mean precipitation biases (mm day^{-1}) over the global tropics from all three CMIP MMEMs—(a) CMIP3, (b) CMIP5, and (c) CMIP6—are shown in Figures 2a2c. There is a strong similarity in the precipitation bias patterns among CMIP3, CMIP5, and CMIP6 models (Figures 2a2c) with a high correlation among them ($R^2 = 0.88$ between CMIP3 and CMIP5, $R^2 = 0.86$ between CMIP5 and CMIP6, and $R^2 = 0.76$ between CMIP3 and CMIP6). This again indicates that all three generations of CMIP models share similar systematic precipitation errors. For all model generations, positive precipitation biases are found over the north Pacific (10°15°N), the south central and eastern Pacific (5°20°S), the equatorial South Atlantic (equator15°S), the equatorial western Indian Ocean, and the oceanic parts of the Maritime Continents. On the other hand, negative precipitation biases exist in the equatorial North Atlantic (equator5°N), the Central America, the Amazonia, the South Asia including the Bay of Bengal, the land parts of the Maritime Continents, and the equatorial western Pacific. In particular, the positive precipitation biases over the south central and eastern Pacific, the equatorial south Atlantic, the equatorial western Indian, and the north Pacific (10°15°N) as well as the negative precipitation biases in the Amazonia and the South Asia including the Bay of Bengal are more than the observational uncertainty. The positive precipitation bias over the north Pacific around 15°N and negative precipitation bias over the north Pacific around 5°N are related to the fact that the NH Pacific ITCZ in the models is more to the north relative to observations. The positive precipitation bias over the south central and eastern Pacific is an indicator of the double-ITCZ bias in the models (e.g., Adam et al., 2018; Hwang & Frierson, 2013; Li & Xie, 2014; Tian, 2015; Xiang et al., 2017; Zhang et al., 2015). The negative precipitation bias over the equatorial western Pacific is the indicator of the equatorial Pacific cold tongue bias in the models (Li & Xie, 2014; Mechoso et al., 1995). The large positive and negative precipitation biases over the Indo-Pacific warm pool are consistent with the too smooth precipitation pattern in the models. The positive precipitation bias over the equatorial North Atlantic and the negative precipitation bias over the equatorial South Atlantic are consistent with the fact that the Atlantic ITCZ in the models is more to the south relative to observations. This precipitation bias pattern has been well discussed in the literature for CMIP3 and CMIP5 models.

To examine the potential improvement of precipitation simulations among CMIP3, CMIP5, and CMIP6 models, differences of the absolute long-term precipitation biases over the global tropics among CMIP3/5/6 MMEMs are shown in Figures 2d2f: (d) CMIP5–CMIP3, (e) CMIP6–CMIP3, and (f) CMIP6–CMIP5. If the difference of the absolute biases is negative, then the precipitation bias decreases and the model gets better, vice versa for the positive difference. Comparing CMIP3 and CMIP5, the precipitation bias decreases and the model gets better in some regions (e.g., the equatorial western Pacific near Papua New Guinea, the Amazonia, and the equatorial North Atlantic), but the precipitation bias increases and the model gets worse in some other regions (e.g., the equatorial south Indian and the equatorial Atlantic). However, the changes are rather small over the central and eastern Pacific. Comparing CMIP5 and CMIP6, the precipitation bias decreases, and the model seems to get better in most regions (e.g., the south central and eastern Pacific, the north central and western Pacific, and the southwestern Indian Ocean) except for southeastern Indian Ocean. In particular, the decrease of precipitation bias over the south central and eastern Pacific indicates that the double-ITCZ bias might be reduced from CMIP5 to CMIP6.

To quantify the possible reduction of the double-ITCZ bias from CMIP3 to CMIP5 and from CMIP5 to CMIP6, Figure 3 shows the global, Pacific, and Atlantic TPAIs (ac) and EPIs (df), the SIIP (g), and the SIIA (h) from observations (Obs), MMEMs, standard deviations (SDs), lowest-3-model means (L3MMs), highest-3-model means (H3MMs), and all individual models. (The actual numerical values are listed in supporting information Table S2). The observed global, Pacific, and Atlantic TPAI values are ~0.20, 0.32, and 1.10, respectively, meaning that the NH global, Pacific, and Atlantic tropical mean precipitation is about

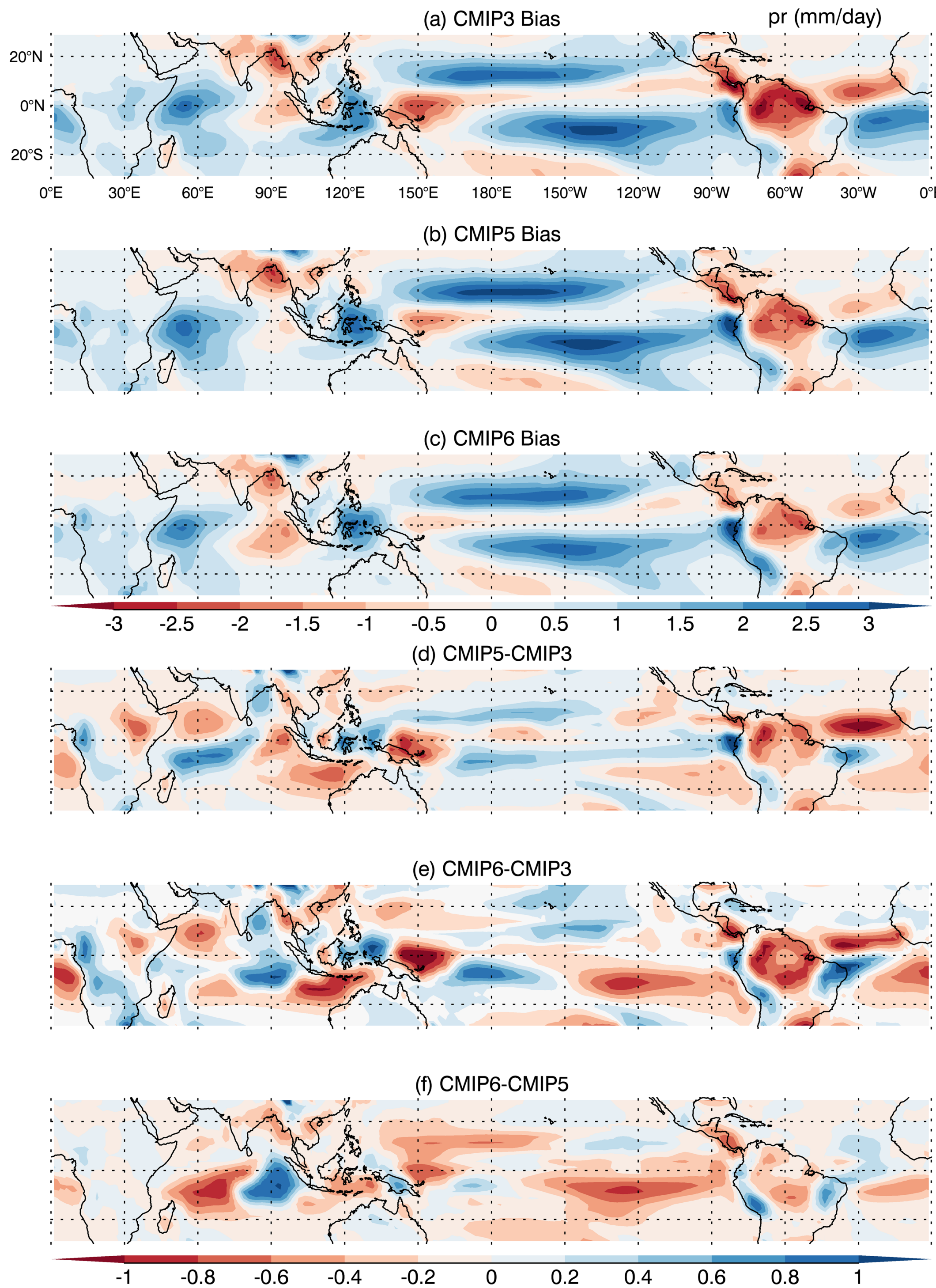

Figure 2. Long-term annual mean precipitation bias (model-observation, mm day^{-1}) over the global tropics (30°S to 30°N) from (a) CMIP3 MMEM, (b) CMIP5 MMEM, and (c) CMIP6 MMEM. Difference of the absolute long-term precipitation bias over the global tropics (30°S to 30°N) among generations of CMIP models: (d) CMIP5–CMIP3, (e) CMIP6–CMIP3, and (f) CMIP6–CMIP5.

20%, 32%, and 110%, respectively, larger than the SH global, Pacific, and Atlantic tropical mean precipitation. The uncertainties of the observed global, Pacific, and Atlantic TPAI values are about 0.04, 0.06, and 0.22, respectively. We have assumed that the underlying RBE of each precipitation index is the

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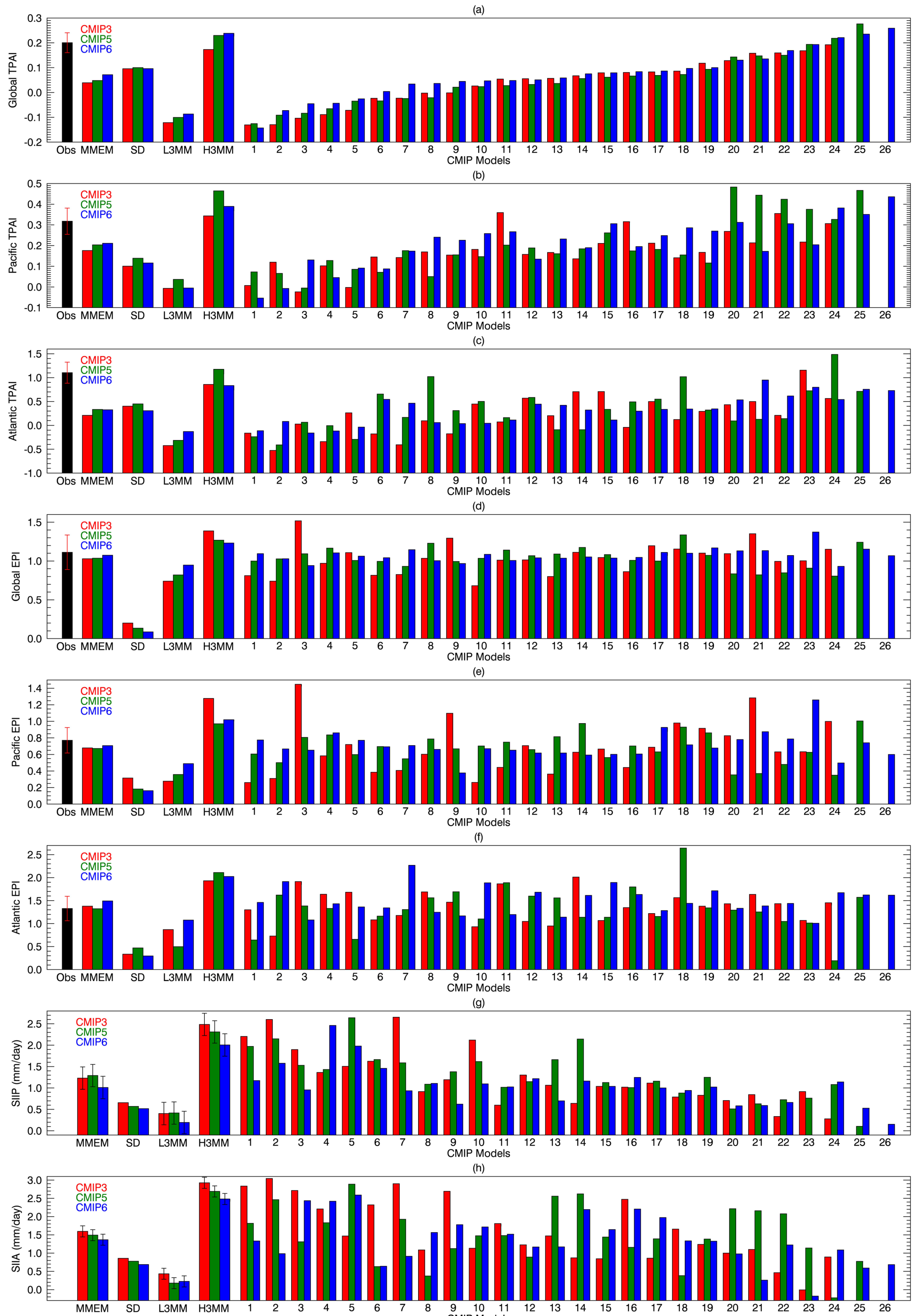

Figure 3. The global (a), Pacific (b), and Atlantic (c) tropical precipitation asymmetry indices (TPAIs); the global (d), Pacific (e), and Atlantic (f) equatorial precipitation indices (EPIs); the southern ITCZ index over the Pacific (SIIP) (g); and the southern ITCZ index over the Atlantic (SIIA) (h) from observations (Obs, none for panels g and h), multi-model ensemble means (MMEMs), standard deviations (SDs), lowest-3-model means (L3MMs), highest-3-model means (H3MMs), and all individual CMIP models (narrow bars). Red bars denote CMIP3 models, green bars denote CMIP5 models, and blue bars denote CMIP6 models. Their actual numerical values are listed in supporting information Table S2. The model numbers on the horizontal axis are the same model numbers listed in supporting information Table S1 and sorted in an ascending order by the global TPAI values shown in (a) and Table S2 for CMIP3, CMIP5, and CMIP6 models, respectively.

same as the observation (20%) (Adler et al., 2012). Thus, for each precipitation index, we simply multiply the precipitation index value with 20% to get its uncertainty (absolute bias error, same thereafter). For individual models, the global TPAI value varies from ~−0.15 to ~0.28 with a same standard deviation of ~0.10 among CMIP3/5/6 models, indicating a big inter-model spread of the double-ITCZ bias in all three generations of CMIP models (Tian, 2015). The L3MM global TPAI value is ~−0.10, indicating the SH tropical mean precipitation is higher than the NH tropical mean precipitation and the severe double-ITCZ bias exists in these models (worst models). The L3MM global TPAI value slightly increases from CMIP3 (−0.12) to CMIP5 (−0.10) and from CMIP5 (−0.10) to CMIP6 (−0.09). The H3MM global TPAI value is close to the observation (0.2), indicating the double-ITCZ bias is small in these models (best models). The H3MM global TPAI value slightly increases from CMIP3 (0.17) to CMIP5 (0.23) and from CMIP5 (0.23) to CMIP6 (0.24). The ranges of the model TPAI values are very similar among CMIP3/5/6 models. For most models, the model global TPAI is smaller or much smaller than the observation (0.2). The MMEM global TPAI value is only ~0.05, indicating the SH and NH tropical mean precipitations are almost comparable due to the double-ITCZ bias in the models. The MMEM global TPAI value slightly increases from CMIP3 (0.04) to CMIP5 (0.05) and to CMIP6 (0.07), indicating that the double-ITCZ bias is slightly reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6. Nevertheless, they are still much smaller than the observation (0.2). The above descriptions can also apply to the Pacific and Atlantic TPAI results except that the L3MM Pacific TPAI values, the H3MM Pacific and Atlantic TPAI values slightly decrease from CMIP5 to CMIP6. In addition, the differences between the model and observed TPAI values are even larger over the Atlantic due to the fact that the Atlantic ITCZ in the models is more to the south relative to observations.

The observed global, Pacific, and Atlantic EPI values are 1.11, 0.77, and 1.33 with uncertainties of about 0.22, 0.15, and 0.26, respectively. The equatorial mean precipitation is slightly higher than the tropical mean precipitation over the whole longitudes and over the Atlantic but smaller over the Pacific due to the existence of the equatorial Pacific cold tongue. The MMEM global EPI value is slightly smaller (~1.05) than the observation (1.11), indicating the zonal mean equatorial precipitation is slightly underestimated in the models. This is also true for the Pacific EPI, but the opposite is true for the Atlantic EPI, implying that the underestimation of the zonal mean equatorial precipitation may be due mainly to the equatorial Pacific cold tongue bias in the models. The MMEM global EPI values slightly increase from CMIP3 (1.03) to CMIP5 (1.04) and to CMIP6 (1.07). The same is also true for the MMEM Pacific EPI. This indicates that the equatorial Pacific cold tongue bias is slightly reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6. The model Atlantic EPI is larger than the observation, and CMIP6 models seem to get worse from CMIP3 or CMIP5 models. For individual models, the model global EPI value varies from ~0.7 to ~1.5, indicating a big inter-model spread of the equatorial cold tongue bias in all three generations of CMIP models. The L3MM global EPI values are ~0.8, indicating the severe underestimation of the zonal mean equatorial precipitation in these models, and they slightly increase from CMIP3 (0.74) to CMIP5 (0.82) and from CMIP5 (0.82) to CMIP6 (0.95). The H3MM global EPI values are ~1.3, indicating the overestimation of the zonal mean equatorial precipitation in these models, and they slightly decrease from CMIP3 (1.39) to CMIP5 (1.27) and from CMIP5 (1.27) to CMIP6 (1.23). This indicates that the ranges of the model global EPI values become narrower from CMIP3 to CMIP5 and from CMIP5 to CMIP6. This is also reflected by the decrease of the standard deviations of model global EPIs from CMIP3 (0.20) to CMIP5 (0.14) and from CMIP5 (0.14) to CMIP6 (0.09). This indicates that the inter-model spread of the equatorial Pacific cold tongue bias is reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6.

The uncertainty of the observed SIIP value is about 0.26 mm day^{-1}. The model SIIP values vary from ~0.1 to ~2.6 mm day^{-1} in all models, implying that a big inter-model spread of the double-ITCZ bias over the Pacific exists in all three generations of models. This is consistent with the conclusion based on the TPAI results. However, the standard deviations of model SIIP for each generation slightly decrease from CMIP3 (0.66) to CMIP5 (0.57) and from CMIP5 (0.57) to CMIP6 (0.52). The MMEM SSIP value is ~1.23 mm day^{-1} for CMIP3, ~1.29 mm day^{-1} for CMIP5, and ~1.01 mm day^{-1} for CMIP6. This indicates that the double-ITCZ bias over the Pacific is slightly increased from CMIP3 to CMIP5 but slightly reduced from CMIP5 to CMIP6. However, the difference of the model SIIP values is within the SIIP uncertainty. The L3MM global SIIP values are ~0.3 mm day^{-1}, indicating the annual mean precipitation over the southeastern Pacific is well simulated in these models (best models). They stay almost the same from CMIP3 (0.40) to CMIP5 (0.42) and slightly decrease from CMIP5 (0.42) to CMIP6 (0.19). The H3MM global SIIP values are

~2.3 mm day^{-1}, indicating the annual mean precipitation over the southeastern Pacific is highly overestimated in these models (worst models). However, they slightly decrease from CMIP3 (2.49) to CMIP5 (2.31) and from CMIP5 (2.31) to CMIP6 (2.01). This indicates that the double-ITCZ bias over the Pacific for the worst models is reduced slightly from CMIP3 to CMIP5 and from CMIP5 to CMIP6. The Pacific TPAI and SIIP results differ from each other regarding the change of the double-ITCZ bias over the Pacific from CMIP3 to CMIP5. However, both the Pacific TPAI and SIIP results agree on the decrease of the double-ITCZ bias over the Pacific from CMIP5 to CMIP6, indicating that such a decrease is a robust result that does not depend on the double-ITCZ bias index used.

The uncertainty of the observed SIIA value is about 0.15 mm day^{-1}. The model SIIA values vary from ~0.0 to ~3.0 mm day^{-1} in all models, implying a big inter-model spread of the double-ITCZ bias over the Atlantic in all three generations of CMIP models too. The standard deviations of model SIIA for each generation also slightly decrease from CMIP3 (0.87) to CMIP5 (0.78) and from CMIP5 (0.78) to CMIP6 (0.69). The MMEM SSIA value is ~1.60 mm day^{-1} for CMIP3, ~1.49 mm day^{-1} for CMIP5, and ~1.37 mm day^{-1} for CMIP6. This indicates that the double-ITCZ bias over the Atlantic is slightly reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6. Again, the difference of the model SIIA values is within the SIIA uncertainty. The L3MM global SIIA values are ~0.2 mm day^{-1}, indicating the annual mean precipitation over the South Atlantic is well simulated in these models (best models). They slightly decrease from CMIP3 (0.43) to CMIP5 (0.18) and stay almost the same from CMIP5 (0.18) to CMIP6 (0.22). The H3MM global SIIA values are ~2.7 mm day^{-1}, indicating the annual mean precipitation over the South Atlantic is highly overestimated in these models (worst models). However, they slightly decrease from CMIP3 (2.93) to CMIP5 (2.69) and from CMIP5 (2.69) to CMIP6 (2.48). This indicates that the double-ITCZ bias over the Atlantic for the worst models is slightly reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6. The Atlantic TPAI and SIIA results agree on the decrease of the double-ITCZ bias over the Atlantic from CMIP3 to CMIP5 and from CMIP5 to CMIP6, indicating that such a decrease is a robust result that does not depend on the double-ITCZ bias index used.

4. Summary

This study seeks to examine the double-ITCZ bias and its inter-model spread in the latest state-of-the-art climate models for CMIP6 and its possible progress in comparison to their previous generations of models (CMIP3 and CMIP5). To that end, we have analyzed the long-term annual mean tropical precipitations from two observational data sets (GPCP and TRMM) and 75 models including 24 CMIP3 models, 25 CMIP5 models, and 26 CMIP6 models. We have focused on the precipitation and bias (model-observation) maps, several precipitation bias indices that quantify the double-ITCZ bias, and their differences among CMIP3, CMIP5, and CMIP6 models. The seasonal variations of the double-ITCZ bias and precipitation bias in the models are significant, but they are not examined in this paper and should be explored in the future.

We find that CMIP3, CMIP5, and CMIP6 models share similar troublesome systematic errors in long-term annual mean precipitation simulations. In particular, we find that the annual double-ITCZ bias and its big inter-model spread evident in CMIP3 and CMIP5 models persist in CMIP6 models and still remain a serious problem in latest generation of CMIP models. However, the double-ITCZ bias over both the Pacific and Atlantic Oceans is reduced slightly from CMIP5 to CMIP6, and the double-ITCZ bias over the Atlantic is also reduced slightly from CMIP3 to CMIP5 based on the global, Pacific, and Atlantic TPAIs, the SIIP, and the SIIA. The annual equatorial Pacific cold tongue bias evident in CMIP3 and CMIP5 models also persist in CMIP6 models, but its inter-model spread is reduced from CMIP3 to CMIP5 and from CMIP5 to CMIP6 based on the global, Pacific, and Atlantic EPIs.

The persistence of the double-ITCZ and equatorial Pacific cold tongue biases in all three generations of CMIP models is quite alarming considering the vast inter-generational differences and improvements in model spatial and vertical resolutions, convection and cloud parameterization schemes, atmospheric chemistry, land process, and ocean dynamics. It may still take decades to fully eliminate these biases in climate models. However, the slight reduction of the double-ITCZ bias and the inter-model spread of the equatorial Pacific cold tongue bias from CMIP5 to CMIP6 provide us some hope.

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